

# **A Micro-Ultrastable Oscillator (micro-USO) for Micro/Nano Sciencecraft**

**NASA Grant No. NAG5-10395  
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**MICRO-USO ABSTRACT**

FOR NASA's "ABSTRACT COLLECTION AND TRANSMITTAL SYSTEM" (ACTS) at  
<http://proposals.hq.nasa.gov>

Syntonics LLC developed a prototype micro-Ultra Stable Oscillator (micro-USO) under a Space Base Technology Grant (NAG5-10395). Syntonics conducted the micro-USO Program in two phases. In Phase I, we developed a set of verified analytical models (including thermal, electrical, and control models) for a baseline USO, conducted a series of six technology studies, and built three ~900g prototype units. These prototypes provided a tool for evaluating competing design topologies. In Phase II we prepared the conceptual design of a ~100-150g micro-USO.

During Phase I we examined six technology areas to identify advanced technologies suitable for incorporation into the Phase II objective system:

- Alternative Dewar Architectures
- Non-Dewar Architectures for Oven Thermal Isolation
- Reduced Size EEE Components
- Reduced Profile Interconnect Strategies
- Reduced Component Count Circuit Design
- Composite Materials

Three Phase I micro-USO prototypes were fabricated and tested to serve three purposes. First, they provided a hardware test article that was used to validate thermal, mechanical, and electrical models that have been created as tools for developing the objective system. Second, they provided a hardware baseline for testing alternative technologies and architectures that might be applicable to the Phase II micro-USO, which is expected to be substantially smaller than existing flight hardware. Third, these prototypes were used to evaluate three potential resonator designs that are being examined as candidates for use in the objective system.

In Phase II, the conceptual design of a very small micro-USO was developed and extensive thermal analyses were made of the design. The design was prepared to meet specifications developed in concert with technical personnel at NASA Goddard Space Flight Center and to represent the current "state of the art" in USOs for use in space missions. The Phase II design is intended to meet these design goals:

Output Frequency:.....10.000 MHz  
Frequency (Setting) Accuracy: .....5e-8  
Aging Rate: .....5e-10 per day  
Allan Variance (Deviation):  
0.1 sec .....5e-12

1 sec .....	1 e-12
10 sec .....	5 e-13
100 sec.....	5e-13
1000 sec.....	5e-13
SSB Phase Noise:	
1 Hz.....	-110 dBc/Hz
10 Hz.....	-132 dBc/Hz
100 Hz.....	-147 dBc/Hz
1 kHz.....	-155 dBc/Hz
10 kHz.....	-160 dBc/Hz
100 kHz.....	-160 dBc/Hz
Harmonics:.....	< -50 dBc
Spurious Emissions: .....	< -70 dBc
Temperature Sensitivity:.....	5e-12 per °C (20°C to 40°C)
Magnetic Sensitivity:.....	2e-12 per Gauss
Radiation Sensitivity: .....	1e-10 per Rad
Acceleration Sensitivity:.....	2e-9 per g
No. of Outputs:.....	One
Output Power: .....	0 dBm ± 1.0 dB
Output Impedance: .....	50 ohm
Output VSWR:.....	1.25:1
Volume: .....	60 cc
Mass:.....	50 g
Power (Average at 25°C):.....	0.25 W
Power (Max at Turn-On): .....	1 W
Input Voltage: .....	19.5 ± 0.5 VDC
Temperature Range (Operating): .....	-15°C to +66°C
Total Radiation Dose:.....	100 krad
Design Lifetime:.....	5 years
Vibration:.....	Typical Launch Environment
Electromagnetic Compatibility: .....	MIL-SPEC-461C*
In-Rush Current:.....	Less than 2A for 50 ms

**PHASE I TECHNOLOGY STUDIES**

During Phase I we examined six technology areas to identify advanced technologies suitable for incorporation into the Phase II objective system:

- Alternative Dewar Architectures
- Non-Dewar Architectures for Oven Thermal Isolation
- Reduced Size EEE Components
- Reduced Profile Interconnect Strategies
- Reduced Component Count Circuit Design
- Composite Materials

**Alternative Dewar Architectures**

A study was conducted to develop a lightweight alternative Dewar for use in the micro-USO. Pursuant to this study, thermal and mechanical models of a small, lightweight Dewar were developed and a detailed design was produced. It was concluded that a small aluminum Dewar could replace the previous combination of an aluminum housing and titanium Dewar. The Dewar was shortened considerably, removing a long insulating plug that drove the length of the original Dewar. The manufactured sample, however, was flawed and produced inferior thermal isolation. A second prototype is being built which will remedy the shortcomings identified in the first attempt. It is hoped that this alternative lightweight Dewar will validate this approach to USO construction, as the use of a Dewar is very advantageous in many respects. It is unlikely that the alternative Dewar architecture will be incorporated into the Phase 2 Micro USO.

**Non-Dewar Architectures for Oven Thermal Isolation**

A second study was conducted to develop an alternative thermal isolation architecture that eliminates the Dewar altogether. This study concluded an alternative architecture that completely eliminates the Dewar is feasible. The Non-Dewar architecture suspends the oven by Kevlar™ threads. Proper selection of materials and finishes on the exterior of the oven and the interior of the string suspension system minimizes radiative coupling. Placing the entire structure within an evacuated housing eliminates convective and conductive coupling due to air. Thermal isolation performance is dominated by the conductive path from the environment to the oven assembly via the wiring harness.

**Reduced Size EEE Components**

A third study was conducted to select reduced-size components to replace as many USO EEE parts as possible, reducing overall PCB area. Pursuant to this study, PSPICE modeling of the USO was conducted and a parts stress analysis was performed. This modeling and analysis revealed that most of the resistors used in the USO are dissipating less than 5 mW in a package designed to handle 50 mW (RM0805 style military chip resistors). Most of these resistors can be easily replaced with RM0603 or RM0402 style resistors, providing as much as a 4:1 reduction in PCB real estate for those components. As resistors account for the majority of the EEE components in the USO PCBs, this is an encouraging finding. Similar reductions in chip capacitors are probably not possible due to concerns about spaceflight use of low-voltage capacitors that can grow shorts (whiskers) in space without sufficient voltage to clear the shorts (the USO oscillator runs on only 10 VDC). Most of the relatively few semiconductors in the USO can be replaced with small surface-mount military UB packages using off-the-shelf suppliers. Some of the remaining semiconductors can be replaced with custom-packaged surface mount semiconductors at some increase in cost. The overall conclusion of this study is that substantial reductions in PCB area, perhaps as much as 50%, can be realized by using reduced-size EEE components. This strategy will be utilized in the Phase 2 Micro-USO.

#### **Reduced Profile Interconnect Strategies**

A fourth study was conducted to identify advanced interconnect strategies and PCB technologies to reduce overall PCB size. This study, led by Binh Q. Le of The Johns Hopkins University Applied Physics Laboratory, examined a number of relevant technologies including: direct chip attach ("Chip On Board"); multilayer PCBs and blind or buried vias; embedded passive components; and rigid-flex PCBs. This was a thorough study, however, some of the candidate techniques have associated costs and risks that are not commensurate with the decrease in PCB area afforded. It is possible that multilayer PCBs and/or blind or buried vias may be utilized, but the other techniques will most likely not be incorporated into the Phase 2 Micro USO.

#### **Reduced Component Count Circuit Design**

A fifth study was conducted to identify possible simplifications in the USO PCBs or reductions in the number of EEE components as an alternative means of reducing overall PCB area. Several modest simplifications have been identified that will result in an overall reduction. These potential changes will be prototyped at the beginning of the Phase 2 design process to confirm the modeling used to explore the potential changes. If the prototypes perform as well as the models, it is likely that these reductions in component count will be incorporated into the Phase 2 Micro USO.

#### **Composite Materials**

A sixth study was conducted to identify materials that might save volume or weight in the Micro-USO. A database of materials and their properties was created collecting information relating to density, thermal coefficient of expansion, specific heat, thermal conductivity, and emissivity of a variety of materials. While no material was identified as a replacement for the aluminum or copper

used to fabricate the oven, a number of these materials have very interesting properties and may eventually find their way into the Phase 2 Micro USO in one capacity or another.

**PHASE I MICRO-USO PROTOTYPE**

A Phase I micro-USO prototype was designed, analyzed and tested.

**Phase I micro-USO design drawings**

These design drawings were developed:

**Document Tree for Phase 1 Micro-USO  
Top-Level Assembly Rev. UG - January 30, 2002**

**ITEM NUMBERS****DESCRIPTION****Top Level Assembly**

AAA-EMA-USO001-0001

ASY-EMA-USO001-0001

BOM-EMA-USO001-0001

INT-EMA-USO001-0001

TST-EMA-USO001-0001

PPP-CVR-USO001-0001

FAB-CVR-USO001-0001

PPP-PNL-USO001-0002

FAB-PNL-USO001-0002

**Connector Panel Assembly**

AAA-EMA-PNLUSO-0001

ASY-EMA-PNLUSO-0001

BOM-EMA-PNLUSO-0001

PPP-PNL-USO001-0001

FAB-PNL-USO001-0001

AAA-CBA-CX0001-0004

ASY-CBA-CX0001-0000

BOM-CBA-CX0001-0004

TST-CBA-CX0001-0000

AAA-CBA-MC0001-0018

ASY-CBA-MC0001-0000

BOM-CBA-MC0001-0018

TST-CBA-MC0001-0000

Assembly, Top Level, Baseline Micro-USO

Assembly Drawing, Baseline Micro-USO Top Level Assembly

Bill of Material, Baseline Micro-USO Top Level Assembly

Interconnect Drawing, Baseline Micro-USO Top Level Assembly

Test Procedure, Baseline Micro-USO Top Level Assembly

Dewar Chamber Cover, Micro-USO

Fabrication Drawing, Dewar Chamber Cover, Micro-USO

Chase Cover Panel, Micro-USO

Fabrication Drawing, Chase Cover Panel, Micro-USO

Assembly, Connector Panel, Micro-USO

Assembly Drawing, Connector Panel Assembly, Micro-USO

Bill of Material, Connector Panel Assembly, Micro-USO

Connector Panel, Micro-USO

Fabrication Drawing, Connector Panel, Micro-USO

Assembly, Cable, SMA Pigtail, 4-inch long

Assembly Drawing, Cable, SMA Pigtail

Bill of Material, Assembly, Cable, SMA Pigtail

Test Procedure, Assembly, Cable, SMA Pigtail

Assembly, Cable, Pre-Fab Micro-D, 15 conductor, 18-inch long

Assembly Drawing, Cable, Pre-Fab Micro-D, 15 conductor

Bill of Material, Assembly, Cable, Pre-Fab Micro-D, 15 conductor

Test Procedure, Assembly, Cable, Pre-Fab Micro-D, 15 conductor

## Isolator Tower Assembly

AAA-MCA-TWRISO-0001

ASY-MCA-TWRISO-0001

BOM-MCA-TWRISO-0001

PPP-BKT-USO001-0001

FAB-BKT-USO001-0001

Assembly, Bracket, Vibration Isolator Tower, Micro-USO  
Assembly Drawing, Vibration Isolator Tower Bracket, Micro-USO  
Bill of Material, Assembly, Vibration Isolator Tower Bracket, Micro-USO  
Bracket, Vibration Isolator Tower, Micro-USO  
Fabrication Drawing, Bracket, Vibration Isolator Tower, Micro-USO

## Dewar Assembly

AAA-EMA-DWR502-0001

ASY-EMA-DWR502-0001

BOM-EMA-DWR502-0001

TST-EMA-DWR502-0001

PPP-HSG-DWR105-0001

FAB-HSG-DWR105-0001

PPP-HSG-DWR107-0001

FAB-HSG-DWR107-0001

PPP-HSG-DWR108-0001

FAB-HSG-DWR108-0001

Assembly, Dewar  
Assembly Drawing, Dewar Assembly  
Bill of Material, Dewar Assembly  
Test Procedure, Dewar Assembly  
Housing, Dewar  
Fabrication Drawing, Dewar Housing  
Lid, Dewar Housing, Micro-USO  
Fabrication Drawing, Lid, Dewar Housing, Micro-USO  
Adapter, Dewar Housing Lid  
Fabrication Drawing, Dewar Housing Lid Adapter

## Oven Assembly

AAA-EMA-OVN505-0001

ASY-EMA-OVN505-0001

BOM-EMA-OVN505-0001

INT-EMA-OVN505-0001

TST-EMA-OVN505-0001

ASM-EMA-OVN505-0001

PPP-HSG-OVN005-0002

FAB-HSG-OVN005-0002

Assembly, Oven, Micro-USO  
Assembly Drawing, Oven Assembly, Micro-USO  
Bill of Material, Oven Assembly, Micro-USO  
Interconnect Diagram, Oven Assembly, Micro-USO  
Test Procedure, Oven Assembly, Micro-USO

Cap, Oven, Micro-USO  
Fabrication Drawing, Oven Cap, Micro-USO

## Heater Assembly

AAA-EMA-HTR001-0001

ASY-EMA-HTR001-0001

BOM-EMA-HTR001-0001

TST-EMA-HTR001-0001

ASM-EMA-HTR001-0001

GEN-STD-000000-9545

PPP-HSG-OVN005-0001

FAB-HSG-OVN005-0001

Heater Housing, Thermistor & Heater Winding  
Assembly, Heater, Micro-USO  
Assembly Drawing, Heater, Micro-USO  
BOM, Heater, Micro-USO  
Test Procedure, Heater, Micro-USO  
Assembly Procedure, Heater, Micro-USO  
Procedure, use of epoxy adhesives  
Housing, Oven, Main, Micro-USO  
Fabrication Drawing, Main Oven Housing, Micro-USO

## Oscillator Assembly

AAA-EMA-OSC001-0001

ASY-EMA-OSC001-0001

BOM-EMA-OSC001-0001

INT-EMA-OSC001-0001

TST-EMA-OSC001-0001

Crystal, Crystal Cap & A1 PCB Assembly  
Assembly, Crystal, Crystal cap & A1 PCB  
Assembly Drawing, Crystal, Crystal cap & A1 PCB assembly  
Bill of Material, Crystal, Crystal cap & A1 PCB assembly  
Interconnect Diagram, Crystal, Crystal cap & A1 PCB assembly  
Test Procedure, Crystal, Crystal cap & A1 PCB assembly

## Resonator Assembly

AAA-EMA-XTL001-0001

ASY-EMA-XTL001-0001

BOM-EMA-XTL001-0001

INT-EMA-XTL001-0001

TST-EMA-XTL001-0001

ASM-EMA-XTL001-0001

GEN-STD-000000-9545

PPP-HSG-OVN005-0003

FAB-HSG-OVN005-0003

Crystal & Crystal Cap Assembly  
Assembly, Crystal & Crystal Cap  
Assembly Drawing, Crystal, Crystal cap & A1 PCB assembly  
Bill of Material, Crystal, Crystal cap & A1 PCB assembly  
Interconnect Diagram, Crystal, Crystal cap & A1 PCB assembly  
Test Procedure, Crystal, Crystal cap & A1 PCB assembly  
Assembly Procedure, Resonator Assembly  
Procedure, use of epoxy adhesives  
Crystal Chamber Cap, HC-40 Resonator  
Fabrication Drawing, Crystal Chamber Cap, HC-40 Resonator

	<p><b><u>Oscillator PCB (A1) Assembly</u></b>  AAA-PCA-A01502-0001      ASY-PCA-A01502-0001      BOM-PCA-A01502-0001      TST-PCA-A01502-0001      SCH-PCA-A01502-0001      PPP-PCB-A01002-0001      (GERBER FILES)      FAB-PCB-A01002-0001  AAA-XFR-T00006-0000      ASY-XFR-T00006-0000      BOM-XFR-T00006-0000  AAA-XFR-T00009-0000      ASY-XFR-T00009-0000      BOM-XFR-T00009-0000</p> <p><b><u>Heater Control PCB (A2) Assembly</u></b>  AAA-PCA-A02502-0001      ASY-PCA-A02502-0001      BOM-PCA-A02502-0001      TST-PCA-A02502-0001      SCH-PCA-A02502-0001      PPP-PCB-A02002-0001      (GERBER FILES)      FAB-PCB-A02002-0001</p> <p><b><u>Service PCB (A4) Unit Assembly</u></b>  AAA-EMA-SVCPA-0001      ASY-EMA-SVCPA-0001      BOM-EMA-SVCPA-0001      INT-EMA-SVCPA-0001      TST-EMA-SVCPA-0001      PPP-HSG-USO001-0001      FAB-HSG-USO001-0001</p> <p><b><u>Service PCB (A4) Assembly</u></b>  AAA-PCA-A04002-0001      ASY-PCA-A04002-0001      BOM-PCA-A04002-0001      TST-PCA-A04002-0001      SCH-PCA-A04002-0001      PPP-PCB-A04002-0001      (GERBER FILES)      FAB-PCB-A04002-0001  AAA-XFR-T00004-0000      ASY-XFR-T00004-0000      BOM-XFR-T00004-0000  AAA-XFR-T00005-0000      ASY-XFR-T00005-0000      BOM-XFR-T00005-0000</p> <p><b><u>Double Half-Width PCB (Multiplier/Amplifier -- A7/A8) Unit Assembly</u></b>  AAA-EMA-DHWPCA-0001      ASY-EMA-DHWPCA-0001      BOM-EMA-DHWPCA-0001      INT-TST-DHWPCA-0001      TST-EMA-DHWPCA-0001      PPP-HSG-USO001-0002      FAB-HSG-USO001-0002</p>	<p>Assembly, A1 PCB  Assembly Drawing, Oscillator PCB  Bill of Material, Oscillator PCB Assembly  Test Procedure, Oscillator PCB Assembly  Schematic, Oscillator PCB  Bare PCB, Oscillator PCB  (OrCAD electronics files only)  Fabrication Drawing, Oscillator PCB  Assembly, Transformer, Torroidal  Assembly Drawing, Transformer, Torroidal  Bill of Material, Transformer Assembly, Torroidal  Assembly, Transformer, Torroidal  Assembly Drawing, Transformer, Torroidal  Bill of Material, Transformer Assembly, Torroidal</p> <p>Assembly, Heater Control PCB  Assembly Drawing, Heater Control PCB Assembly  Bill of Material, Heater Control PCB Assembly  Test Procedure, Heater Control PCB Assembly  Schematic, Heater Control PCB Assembly  Bare PCB, Heater Control  (OrCAD electronics files only)  Fabrication Drawing, Heater Control PCB</p> <p>Assembly, Service PCB Unit  Assembly Drawing, Service PCB Unit Assembly  Bill of Material, Service PCB Unit Assembly  Interconnect Diagram, Service PCB Unit Assembly  Test Procedure, Service PCB Unit Assembly  Housing, Service PCB Assembly  Fabrication Drawing, Service PCB Housing</p> <p>Assembly, Service Board  Assembly Drawing, Service PCB Assembly  Bill of Material, Service PCB Assembly  Test Procedure, Service PCB Assembly  Schematic, A4 Service PCB  Bare PCB, A4, Service PCB  (OrCAD electronics files only)  Fabrication Drawing, A4 Service PCB  Assembly, Transformer, Torroidal  Assembly Drawing, Transformer, Torroidal  Bill of Material, Transformer Assembly, Torroidal  Assembly, Transformer, Torroidal  Assembly Drawing, Transformer, Torroidal  Bill of Material, Transformer Assembly, Torroidal</p> <p>Assembly, Double Half-Width PCB (Multiplier/Amplifier) Unit  Assembly Drawing, Double Half-Width PCB (Multiplier/Amplifier) Unit  Bill of Material, Double Half-Width PCB (Multiplier/Amplifier) Unit  Interconnect Diagram, Double Half-Width PCB (Multiplier/Amplifier) Unit  Test Procedure, Double Half-Width PCB (Multiplier/Amplifier) Unit  Housing, Double Half-Width PCB  Fabrication Drawing, Double Half-Width PCB Housing</p>
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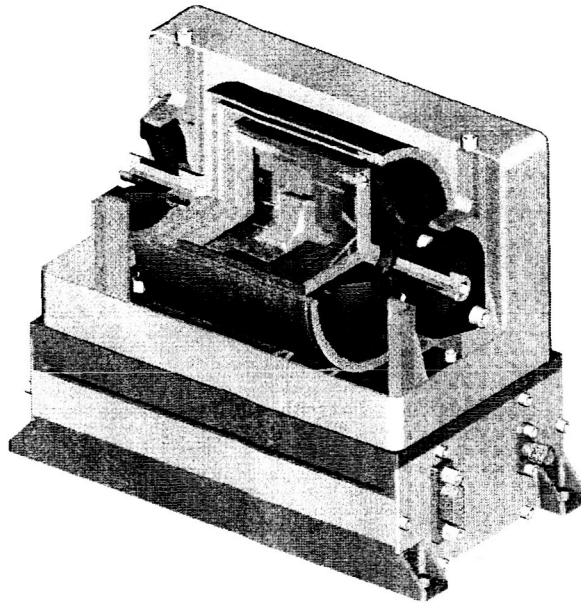


<b><u>Multiplier PCB (A7) Assembly</u></b>	
AAA-PCA-000009-0001	Assembly, Multiplier PCB
ASY-PCA-000009-0001	Assembly Drawing, Multiplier PCB Assembly
BOM-PCA-000009-0001	Bill of Material, Multiplier PCB Assembly
TST-PCA-000009-0001	Test Procedure, Multiplier PCB Assembly
SCH-PCA-000009-0001	Schematic, A8 Buffer Amp PCB
PPP-PCB-000009-0001	Bare PCB, A8, Buffer Amp PCB
(GERBER FILES)	(OrCAD electronics files only)
FAB-PCB-000009-0001	Fabrication Drawing, A8 Buffer Amp PCB
AAA-XFR-T00010-0000	Assembly, Transformer, Torroidal
ASY-XFR-T00010-0000	Assembly Drawing, Transformer, Torroidal
BOM-XFR-T00010-0000	Bill of Material, Transformer Assembly, Torroidal
AAA-XFR-T00008-0000	Assembly, Transformer, Torroidal
ASY-XFR-T00008-0000	Assembly Drawing, Transformer, Torroidal
BOM-XFR-T00008-0000	Bill of Material, Transformer Assembly, Torroidal
<b><u>Amplifier PCB (A8) Assembly</u></b>	
AAA-PCA-000010-0001	Assembly, Amplifier PCB
ASY-PCA-000010-0001	Assembly Drawing, Amplifier PCB Assembly
BOM-PCA-000010-0001	Bill of Material, Amplifier PCB Assembly
TST-PCA-000010-0001	Test Procedure, Amplifier PCB Assembly
SCH-PCA-000010-0001	Schematic, Amplifier PCB Assembly
PPP-PCB-000010-0001	Bare PCB, Amplifier
(GERBER FILES)	(OrCAD electronics files only)
FAB-PCB-000010-0001	Fabrication Drawing, Amplifier PCB
ASY-XFR-T00008-0000	Assembly, Transformer, Torroidal
ASY-XFR-T00005-0000	Assembly Drawing, Transformer, Torroidal
BOM-XFR-T00005-0000	Bill of Material, Transformer Assembly, Torroidal
ASY-IND-T00005-U250	Assembly, Inductor, .25.H, Torroidal
ASY-IND-T00001-2U00	Assembly Drawing, Inductor, Torroidal
BOM-IND-T00001-2U00	Bill of Material, Inductor Assembly, Torroidal
<b><u>Power Supply PCB (A6) Unit Assembly</u></b>	
AAA-EMA-PWSPCA-0001	Assembly, Power Supply PCB Unit
ASY-EMA-PWSPCA-0001	Assembly Drawing, Power Supply PCB Unit Assembly
BOM-EMA-PWSPCA-0001	Bill of Material, Power Supply PCB Unit Assembly
INT-TST-PWSPCA-0001	Interconnect Diagram, Power Supply PCB Unit Assembly
TST-EMA-PWSPCA-0001	Test Procedure, Power Supply PCB Unit Assembly
PPP-HSG-USO001-0003	Housing, Power Supply PCB
FAB-HSG-USO001-0003	Fabrication Drawing, Power Supply PCB Housing
<b><u>Power Supply PCB (A6) Assembly</u></b>	
AAA-PCA-000008-0001	Assembly Drawing, Power Supply PCB
ASY-PCA-000008-0001	Bill of Material, Power Supply PCB
BOM-PCA-000008-0001	Test Procedure, Power Supply PCB
TST-PCA-000008-0001	Schematic, Power Supply PCB
SCH-PCA-000008-0001	Bare PCB Power Supply
PPP-PCB-000008-0001	(OrCAD electronics files only)
(GERBER FILES)	Fabrication Drawing, Power Supply PCB
FAB-PCB-000008-0001	

The following figures illustrates the Phase I prototype design and show the prototype hardware.

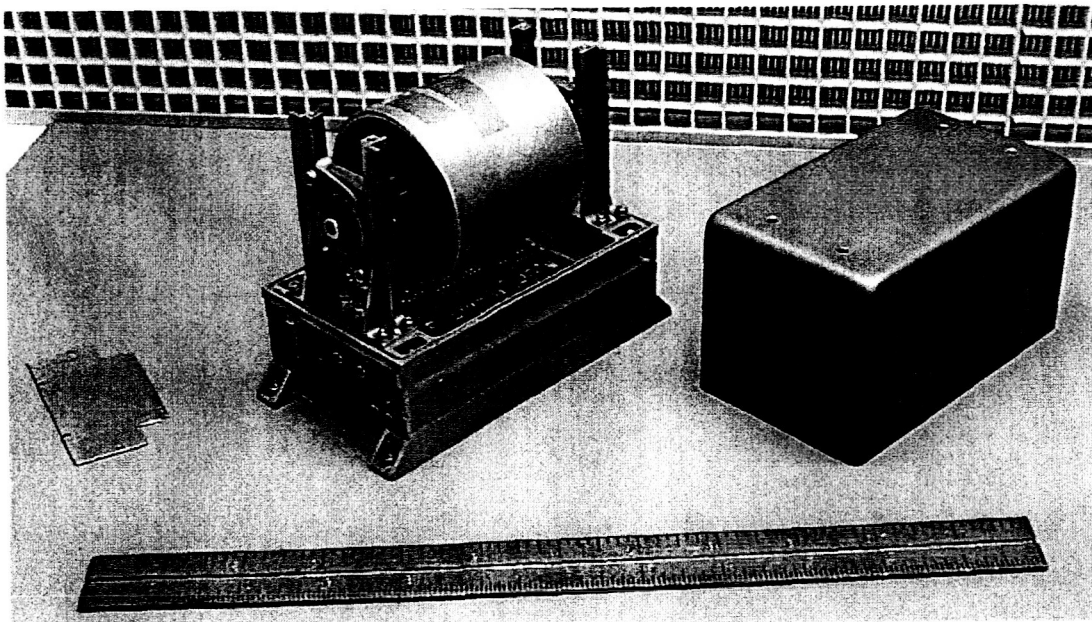
**Figure 1. Solid Model of Phase I micro-USO design**

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**Figure 2. Phase I Prototype Unit**

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**PHASE 1 THERMAL ANALYSIS**

Four detailed thermal studies were conducted of the Phase I design. All thermal analyses were conducted using SINDA/FLUINT. SINDA/FLUINT is a general-purpose finite-differencing thermal/fluid network analyzer. It is used widely among NASA centers to model complex spacecraft thermal control systems, including those which incorporate single- and two-phase fluid loops and capillary devices. This code has evolved over a thirty-year period to become the industry standard for thermal analysis.

**Thermal Study 1—Titanium versus Aluminum Dewar**

A trade study performed to determine the feasibility of constructing the Dewar assembly (APL Drawing Number: 7334-3830) out of aluminum instead of titanium. The intent of this change was to simplify manufacturing and to reduce production costs. For this study, the SINDA thermal model reflected the “baseline” Type-144 Ultra Stable Oscillator (USO) Oscillator Flask Assembly (Drawing No. 7373-3820). This is the flask/Dewar mechanical assembly located within the USO/Frequency Distribution Unit (FDU) Assembly (Drawing No. 7373-3900). The model consisted of thirty-nine nodes with the internal Oven Assembly treated as one node. All analyses were steady state. Not included were the higher-level box thermal model with control logic.

The parametric study was comprised of four cases. Each case was run in a vacuum environment of -20°C. Case 1 reflects the baseline Titanium-Dewar design. Case 2 is the baseline Titanium-Dewar design but for the “Crushed MLI” condition. This condition is a “bounding” condition where the MLI at the mounting cap end is assumed to be crushed and thus ineffective. Case 3 reflects an Aluminum-Dewar design. Case 4 is the aluminum-Dewar design with the “Crushed MLI” condition.

Figure 3 presents the results. For each case, the figure lists several major Flask Assembly components and includes the average temperature of that component as well as the associated maximum predicted temperature gradient. Also shown are the estimated oven heater powers to maintain the oven at +85°C. Based on the analysis, there is no thermal “show stopper” reason for not using aluminum if the current design approach is maintained. It was noted, however, that transient responses might alter these results and a transient analysis was recommended.

**Figure 3. Titanium vs. Aluminum Dewar Thermal Analysis**

ITEM	Node Series	Case #1		Case #2		Case #3		Case #4	
		Avg Temp (C)	Temp Gradient (C)	Avg Temp (C)	Temp Gradient (C)	Avg Temp (C)	Temp Gradient (C)	Avg Temp (C)	Temp Gradient (C)
Flask	5X	-11	0	2	1	-10	0	3	1
Outer Dewar	20X	39	1	19	7	42	1	16	0
Inner Dewar	2X	45	5	24	16	43	1	17	1
Insulator Plug	23X	45	6	39	43	45	6	39	41
Spacer, Flask	8	-10		9		-10		11	
Ribbon Cable	18X	30	79	30	80	30	79	30	80
Inner Cover Dwr Flsk	3	41		11		42		13	
Isolator Assy	80x	-18		-15		-18		-14	
Bottom of Flask	6	-11		3		-10		4	
Power (W)		0.74		1.01		0.74		1.04	

**Thermal Study 2—Dewar Parametric Study in Vacuum**

Study #2 documents the sensitivity of the baseline Titanium-Dewar design to variations in two parameters. The first parameter was the MLI effective emissivity. This was varied from 0.05 to 0.10. The second parameter was the length of the Eccofoam plug. For the study, the same SINDA Titanium-Dewar thermal model as thermal study #1 was used. The model consisted of thirty-nine nodes with the internal Oven Assembly treated as one node. All analyses were steady state. Not included were the higher-level box thermal model with control logic.

Modeling of the reduced Eccofoam plug was done in an approximate fashion. To quickly gain a first order effect and simplify the process, the Dewar model was not reconstructed for a shorter length. Instead, the Eccofoam conductivity was doubled and quadrupled.

The parametric study was comprised of eight cases. Each case was run in a vacuum environment of -20°C. It is important to note that the “AX” cases reflect the “baseline” end cap insulation configuration while the “BX” cases reflect the “Crushed MLI” condition at the end cap.

Case 1 (Case BC) reflects the baseline Titanium-Dewar design with a MLI effective emittance of 0.10. Case 2 (Case BD) is the Aluminum-Dewar design with a MLI effective emittance of 0.05. This is the same case as Case 3 in Reference #1 and was included for comparison purposes. Cases 3 and 4 (Cases BE and BF) reflect the baseline Titanium-Dewar design with the shorter Eccofoam lengths.

Cases 5 through 8 (Cases AC, AD, AE, and AF) reflect the Dewar design with the “Crushed MLI” condition. Case 5 (Case AC) is the Titanium-Dewar design with a MLI effective emittance of 0.10. Case 6 (Case AD) is the Aluminum-Dewar design with a MLI effective emittance of 0.05. This is

the same case as Case 4 in Reference #1 and was included for comparison purposes. Cases 7 and 8 (Cases AE and AF) reflect the Titanium-Dewar design with the shorter Eccofoam lengths.

Figure 4 and Figure 5 present the results. For each case, the tables list several major Flask Assembly components and include the average temperature of that component as well as the associated maximum predicted temperature gradient. Also shown are the estimated oven heater powers to maintain the oven at +85°C. Table 2 shows the results for the Baseline cases, i.e. the "AX" cases. Table 3 shows the cases with the "Crushed MLI" at the Mounting Cap end i.e., "BX" cases. The first case shown in each table is the initial starting case against which the other cases should be compared.

Based on the analysis, three conclusions were drawn. First, the current design is relatively insensitive to the effective emittance of the MLI. Second, the current design strongly requires effective insulation at the Mounting Cap end. Third, the current design is relatively insensitive to the length of the Eccofoam Plug as long as the MLI is effective. For a more detailed discussion of the results, see Reference #2.

**Figure 4. Dewar Parametric Study in Vacuum, Table 1**

Table 1  
Summary of Baseline Cases

ITEM	Node Series	Baseline		Case BC		Case BD		Case BE		Case BF	
		Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	-11	0	-4	0	-10	0	-11	0	-11	0
Outer Dewar	20X	39	1	39	2	42	1	39	1	40	1
Inner Dewar	2X	45	5	48	9	43	1	44	4	45	4
Insulator Plug	23X	45	6	47	8	45	6	45	5	45	3
Spacer, Flask	8	-10		-4		-10		-10		-10	
Ribbon Cable	18X	30	79	31	79	30	79	30	79	30	79
Inner Cover Dwr Flsk	3	41		42		42		41		42	
Isolator Assy	80X	-18	0	-16	0	-18	0	-18	0	-18	0
Bottom of Flask	6	-11		-4		-10		-10		-11	
Power (W)		0.74		0.88		0.74		0.74		0.74	

Case BC Baseline Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.1$   
Case BD Baseline Case with Aluminum Dewar, all MLI Effective  $\epsilon = 0.05$   
Case BE Baseline Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.05$ , Eccofoam length 1/2 baseline  
Case BF Baseline Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.05$ , Eccofoam length 1/4 baseline

**Figure 5. Dewar Parametric Study in Vacuum, Table 2**

Table 2  
Summary of Cases with "Crushed MLI" at Mounting Cap End

ITEM	Node Series	Bounding Baseline		Case AC		Case AD		Case AE		Case AF	
		Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)	Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	2	1	7	1	3	1	4	1	9	1
Outer Dewar	20X	19	7	26	9	16	0	21	6	27	5
Inner Dewar	2X	24	16	35	22	17	1	26	14	31	12
Insulator Plug	23X	39	43	42	39	39	41	47	44	53	40
Spacer, Flask	8	9		15		11		12		19	
Ribbon Cable	18X	30	80	31	80	30	79	31	80	31	80
Inner Cover Dwr Flsk	3	11		17		13		15		23	
Isolator Assy	80X	-15		-13	0	-14	0	-14	0	-13	0
Bottom of Flask	6	3		8		4		5		11	
Power (W)		1.01		1.13		1.04		1.07		1.19	

Case AC "Crushed MLI" Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.1$

Case AD "Crushed MLI" Case with Aluminum Dewar, all MLI Effective  $\epsilon = 0.05$

Case AE "Crushed MLI" Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.05$ , Eccofoam length 1/2 baseline

Case AF "Crushed MLI" Case with Titanium Dewar, all MLI Effective  $\epsilon = 0.05$ , Eccofoam length 1/4 baseline

### Thermal Study 3—Titanium versus Aluminum Dewar

Study #3 documents the results of the parametric study conducted with the Dewar thermal model in a +25°C thermal environment. As described in Studies #1 and #2, the SINDA thermal model reflects the "baseline" Type-144 Ultra Stable Oscillator (USO) Oscillator Flask Assembly (Drawing No. 7373-3820). For this analysis, the higher-level box thermal model with control logic was not included. All analyses were steady state.

The parametric study consisted of twenty-four cases. Each case was run in an environment of +25°C. Figure 6 through Figure 10 presents the results. Each table lists several major components of the USO Oscillator Flask Assembly and includes the average temperature of that component as well as the associated maximum predicted temperature gradient.

Figure 6 with Cases 1 through 4 (Cases BG, BH, BI, and BJ) show the influence of air on the baseline Titanium-Dewar design as well as the proposed aluminum-Dewar design. The first two

cases assume a vacuum environment; the second two cases assume ambient air pressure. These results are summarized in Table 4.

Figure 7 with Cases 5 through 8 (Cases AG, AH, AI, and AJ) show the influence of air on the above titanium and aluminum Dewar designs, but for the “Crushed MLI” condition. This condition is a “bounding” condition where the MLI at the mounting cap end is assumed to be crushed and thus ineffective. Similar to Table 4, two of the cases assume a vacuum, and two of the cases assume ambient air pressure. The results for these cases are summarized in Table 5.

Figure 8 with Cases 9 through 14 (Cases BI3, BJ3, BK, BL, BM, and BN) reflect the “baseline” design and all assume ambient air pressure. The first two cases, BI3 and BJ3, are revisions of the in-air cases presented in Table 4. They reflect upgrades to the model. Cases 11 through 14 (BK, BL, BM, and BN) show the first order effect of reducing the Eccofoam length. The effect is considered “first order” because it was achieved assuming an increased Eccofoam conductivity rather than developing a new model for a shorter Dewar/Eccofoam housing. The results for these cases are summarized in Table 6.

Figure 9 with Cases 15 through 20 (Cases AI3, AJ3, AK, AL, AM, and AN) reflect the “Crushed MLI” condition and all assume ambient air pressure. The first two cases, AI3 and AJ3, are revisions of the “Crushed MLI” in-air cases presented in Table 5. They reflect upgrades to the model. Cases 17 through 20 (BK, BL, BM, and BN) are cases that show the first order effect of reducing the Eccofoam length. The effect is considered “first order” because it was achieved assuming an increased Eccofoam conductivity rather than developing a new model for a shorter Dewar/Eccofoam housing. The results for these cases are summarized in Table 7.

Figure 10 with Cases 21 through 24 (Case #'s BI4, BJ4, AI4, and AJ4) represent a further model enhancement. In all four in-air cases, an Eccofoam radial conduction coupling was added in series with the air conduction coupling between the Eccofoam and Dewar housing. These results take precedence over other BI, BJ, AI and AJ results.

Based on the analysis, three conclusions were drawn. First, the power requirements for in-air testing are significantly greater than the vacuum requirements. Second, the design is relatively insensitive to the value of the Eccofoam Plug conductance. Third, the power requirement difference between the Aluminum Dewar and the Titanium Dewar is negligible in a vacuum environment. However, it is significant in air

**Figure 6. Dewar Parametric Study in a +25°C Environment, Table 4**

Summary of Baseline Cases with 25C Environment

ITEM	Node Series	Case BG		Node Series	Case BH		Node Series	Case BI		Node Series	Case BJ	
		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	30	0	5X	30	0	5X	39	1	5X	52	1
Outer Dewar	20X	56	1	20X	58	0	20X	43	0	20X	60	5
Inner Dewar	2X	59	3	2X	58	0	2X	74	31	2X	72	10
Insulator Plug	23X	60	4	23X	60	4	23X	67	30	23X	73	18
Spacer, Flask	8	30		8	30		8	44		8	59	
Ribbon Cable	18X	54	45	18X	54	45	18X	54	46	18X	55	46
Inner Cover Dwr Flsk	3	57		3	58		3	47		3	62	
Isolator Assy	80X	26	0	80X	26	0	80X	28	0	80X	30	0
Bottom of Flask	6	30		6	30		6	40		6	53	
Power (W)		0.44			0.45			1.74			3.04	

Case BG Titanium Dewar in Vacuum with Environment at 25C  
 Case BH Aluminum Dewar in Vacuum with Environment at 25C  
 Case BI Titanium Dewar in Air with Environment at 25C  
 Case BJ Aluminum Dewar in Air with Environment at 25C

**Figure 7. Dewar Parametric Study in a +25°C Environment, Table 5**

Summary of Bounding Cases with 25C Environment

ITEM	Node Series	Case AG		Node Series	Case AH		Node Series	Case AI		Node Series	Case AJ	
		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	36	0	5X	37	1	5X	40	1	5X	52	2
Outer Dewar	20X	46	4	20X	45	0	20X	43	0	20X	60	5
Inner Dewar	2X	49	9	2X	45	1	2X	74	33	2X	72	10
Insulator Plug	23X	57	24	23X	58	23	23X	66	31	23X	74	18
Spacer, Flask	8	40		8	41		8	46		8	61	
Ribbon Cable	18X	54	45	18X	54	45	18X	54	35	18X	55	46
Inner Cover Dwr Flsk	3	42		3	43		3	47		3	62	
Isolator Assy	80X	27	0	80X	27	0	80X	28	0	80X	30	0
Bottom of Flask	6	37		6	37		6	40		6	54	
Power (W)		0.60			0.63			1.76			3.07	

Case AG Titanium Dewar in Vacuum with Environment at 25C "Crushed MLI" at Mounting Cap End  
 Case AH Aluminum Dewar in Vacuum with Environment at 25C "Crushed MLI" at Mounting Cap End  
 Case AI Titanium Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End  
 Case AJ Aluminum Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End



**Figure 8. Dewar Parametric Study in a +25°C Environment, Table 6**

Summary of Baseline Cases in Air

ITEM	Node Series	Case BI3		Node Series	Case BJ3		Node Series	Case BK		Node Series	Case BL		Node Series	Case BM		Node Series	Case BN	
		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	38	1	5X	45	1	5X	38	1	5X	41	1	5X	46	1	5X	45	1
Outer Dewar	20X	45	3	20X	57	4	20X	45	3	20X	44	2	20X	58	6	20X	57	6
Inner Dewar	2X	71	23	2X	66	7	2X	71	26	2X	75	26	2X	66	10	2X	66	10
Insulator Plug	23X	61	20	23X	66	11	23X	62	22	23X	67	23	23X	69	12	23X	70	13
Spacer, Flask	8	45		8	53		8	45		8	47		8	53		8	53	
Ribbon Cable	18X	54	45	18X	54	45	18X	54	45	18X	54	46	18X	54	46	18X	54	46
Inner Cover Dwr Flsk	3	49		3	57		3	48		3	52		3	58		3	58	
Isolator Assy	80X	28	0	80X	29	0	80X	28	0	80X	28	0	80X	29	0	80X	29	0
Bottom of Flask	6	39		6	46		6	39		6	42		6	47		6	46	
Power (W)		1.63			2.35			1.61			1.88			2.37			2.35	

Case BI3 Baseline Titanium Dewar in Air @25C Rev. 3  
Case BJ3 Baseline Aluminum Dewar in Air @25C Rev. 3  
Case BK Baseline Titanium Dewar in Air @25C 1/2 Eccofoam  
Case BL Baseline Titanium Dewar in Air @25C 1/4 Eccofoam  
Case BM Baseline Aluminum Dewar in Air @25C 1/2 Eccofoam  
Case BN Baseline Aluminum Dewar in Air @25C 1/4 Eccofoam

**Figure 9. Dewar Parametric Study in a +25°C Environment, Table 7**

Summary of Bounding Cases in Air

ITEM	Node Series	Case AI3		Node Series	Case AJ3		Node Series	Case AK		Node Series	Case AL		Node Series	Case AM		Node Series		
		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	37	1	5X	45	1	5X	38	1	5X	41	1	5X	45	1	5X	45	2
Outer Dewar	20X	44	1	20X	56	4	20X	44	1	20X	44	1	20X	56	4	20X	57	5
Inner Dewar	2X	69	28	2X	65	8	2X	70	28	2X	74	29	2X	65	8	2X	66	10
Insulator Plug	23X	55	15	23X	62	7	23X	59	20	23X	65	21	23X	65	12	23X	68	11
Spacer, Flask	8	44		8	54		8	44		8	48		8	54		8	59	
Ribbon Cable	18X	54	45	18X	54	45	18X	54	45	18X	54	46	18X	54	45	18X	54	45
Inner Cover Dwr Flsk	3	46		3	56		3	47		3	50		3	57		3	57	
Isolator Assy	80X	27	0	80X	29	0	80X	28	0	80X	28	0	80X	29	0	80X	29	0
Bottom of Flask	6	38		6	46		6	39		6	42		6	46		6	47	
Power (W)		1.55			2.3			1.59			1.87			2.33			2.36	

Case AI3 Titanium Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End Rev. 3  
Case AJ3 Aluminum Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End Rev. 3  
Case AK Titanium Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End 1/2 Eccofoam  
Case AL Titanium Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End 1/4 Eccofoam  
Case AM Aluminum Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End 1/2 Eccofoam  
Case AN Aluminum Dewar in Air with Environment at 25C "Crushed MLI" at Mounting Cap End 1/4 Eccofoam

**Figure 10. Dewar Parametric Study in a +25°C Environment, Table 8**

Summary of in Air Cases with Radial Conduction in Eccofoam

ITEM	Node Series	Case BI4		Node Series	Case BJ4		Node Series	AI4		Node Series	AJ4	
		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)		Avg. Temp. (C)	Temp Gradient (C)
Flask	5X	37	1	5X	44	1	5X	37	1	5X	44	1
Outer Dewar	20X	43	1	20X	56	4	20X	43	0	20X	55	4
Inner Dewar	2X	69	29	2X	65	8	2X	68	30	2X	64	8
Insulator Plug	23X	64	30	23X	69	21	23X	60	24	23X	66	17
Spacer, Flask	8	42		8	52	52	8	42		8	53	
Ribbon Cable	18X	54	46	18X	54	54	18X	54	46	18X	54	46
Inner Cover Dwr Flsk	3	45		3	56		3	44		3	55	
Isolator Assy	80X	27	0	80X	29	0	80X	27	0	80X	29	0
Bottom of Flask	6	38		6	45		6	37		6	46	
Power (W)		1.50			2.25			1.48			2.26	

Case BI4      Baseline Titanium Case with radial conduction in Eccofoam  
Case BJ4      Baseline Aluminum Case with radial conduction in Eccofoam  
Case AI4      Bounding Titanium Case with radial conduction in Eccofoam  
Case AJ4      Bounding Aluminum Case with radial conduction in Eccofoam

#### Thermal Study 4—USO Temperature Sensitivity Analysis

In support of the NASA/Jet Propulsion Laboratory (JPL) Mars Reconnaissance Orbiter program, Syntonics performed a temperature sensitivity study of an Ultra Stable Oscillator (USO) Assembly.<sup>1</sup> The study used a 65-node SINDA/FLUINT transient model and exercised it for a variety of temperature-varying inputs. The model incorporated the oven's dynamic controller. The basic design of the USO oven temperature controller is an integral control action with saturation.

The USO SINDA/FLUINT model consisted of three sub-models. The first sub-model, the Ultra Stable Oscillator/Frequency Distribution Unit Assembly, consisted of eighteen nodes that represented the electronics box structure and electronic cards. The second sub-model, the Oscillator Flask Assembly, consisted of thirty-nine nodes that represented the flask/Dewar mechanical assembly located within the USO Assembly. The flask/Dewar provides the mechanical support and thermal isolation of the crystal oven. The final sub-model, the Oscillator Temperature/Control Assembly, consisted of eight nodes that represented the oven and crystal. This assembly is located within the Dewar. This latter portion of the SINDA model includes a FORTRAN model of the heater control circuitry, so that the overall model reacts dynamically to external temperature inputs.

<sup>1</sup> This sensitivity analysis was performed under JPL Purchase Order 1230482. A summary is included here for completeness, because the work was performed in the same timeframe as the micro-USO work and it is highly relevant.

The heater control circuitry is critical to the overall operation of the USO Assembly. USO performance relies on holding the temperature of the quartz crystal to a tight tolerance. Fortunately, the frequency versus temperature curve for the type of quartz crystals used in precision oscillators has an inflection point in the range of 80-85 C, where the crystal frequency is insensitive to small temperature variations (i.e.,  $df/dT = 0$ ). This is the "turn-over" temperature. By also keeping critical electrical components at the same constant temperature as the quartz crystal, parameter variations due to temperature sensitivity can be effectively eliminated. Thus, the A1 Oscillator and A2 Heater Control Boards are located in the oven with the quartz resonator. The USO heater controller has an integral control action with saturation. Integral controllers have the desirable property of being able to eliminate all residual error in the controlled variable. In this case, assuming the oven heater has sufficient power to overcome heat loss to the environment, the integral controller is capable of driving a particular thermal node to a desired temperature without the residual error from which proportional controllers suffer. The saturation is an inevitable byproduct of the physical circuitry, which has upper and lower voltage limits as determined by the supply voltage(s).

In total, eight cases were examined. Four of the cases had sinusoidal environmental temperature inputs while the remaining four cases had step-temperature inputs.

Transient results show that the control heater assembly and algorithm are capable of maintaining a constant crystal temperature even for large perturbations in the external environment. The maximum temperature variation seen for a 5°C sinusoidal temperature input is  $\pm 0.001^\circ\text{C}$ , or  $0.002^\circ\text{C}$  total amplitude. The maximum temperature variation seen for a 10°C step-temperature input is  $+0.0016^\circ\text{C}$ .

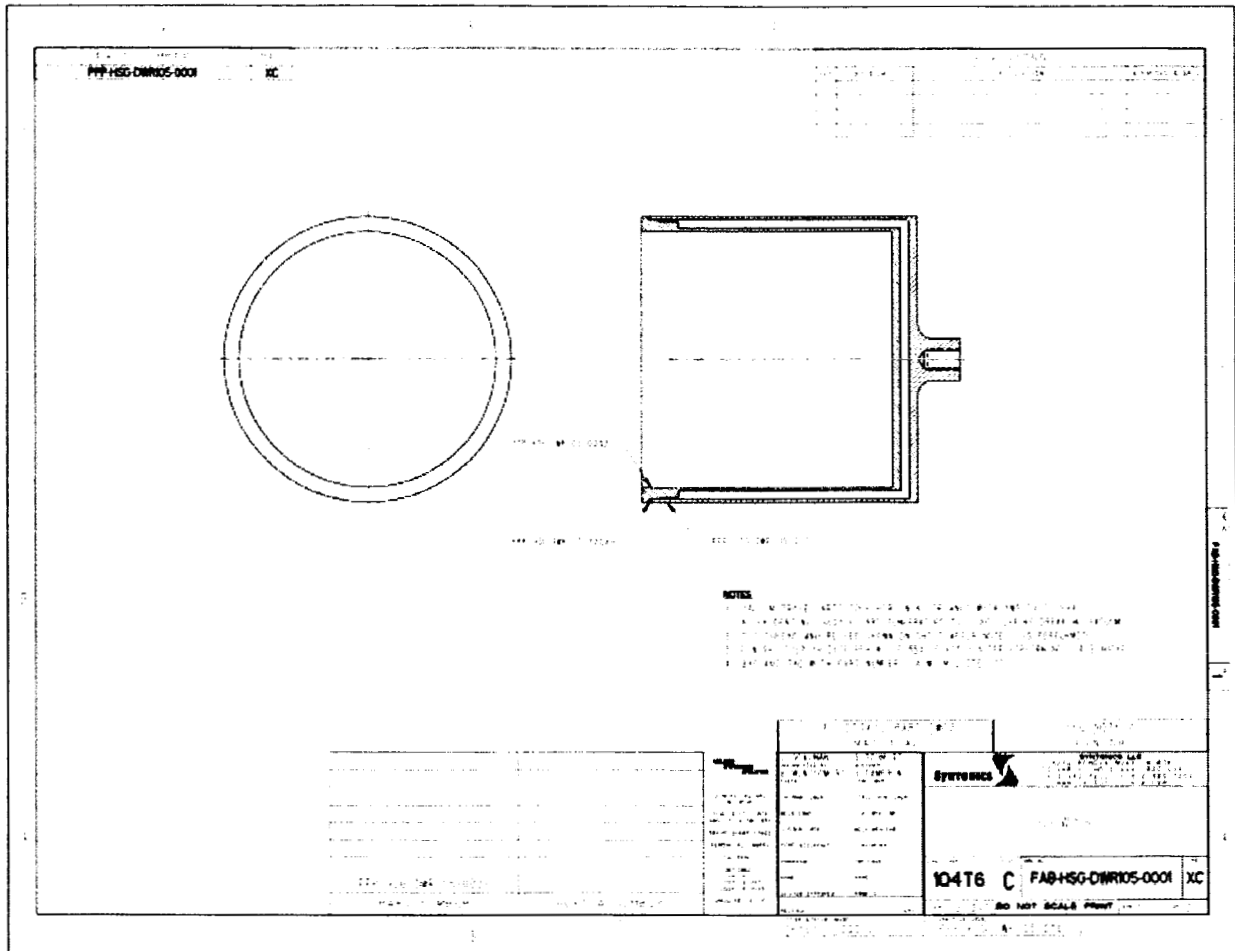
Any frequency disturbance during a rapid, large temperature fluctuation is transient and likely due to temperature effects in the USO electronics outside the oven. The milli-Kelvin temperature pulse that arrives at the crystal causes undetectable frequency disturbances well below the thermal noise floor of the USO and disappears in approximately 1.2 hours.

Outside of the transient effects of rapid temperature change, there is no predictable relationship between temperature and USO frequency. The USOs are highly insensitive to baseplate temperature.

#### **ALTERNATIVE DEWAR DESIGN**

Both aluminum and titanium Dewars were developed for the Phase I design. Figure 11 illustrates the aluminum design. A low-conductivity glass-filled structural plastic (Utem<sup>®</sup>) was used to screw into and close the open end of the Dewar, capturing the oven and its MLI. However, the vacuum brazing process was not perfect and the Dewars leaked, destroying their thermal performance.

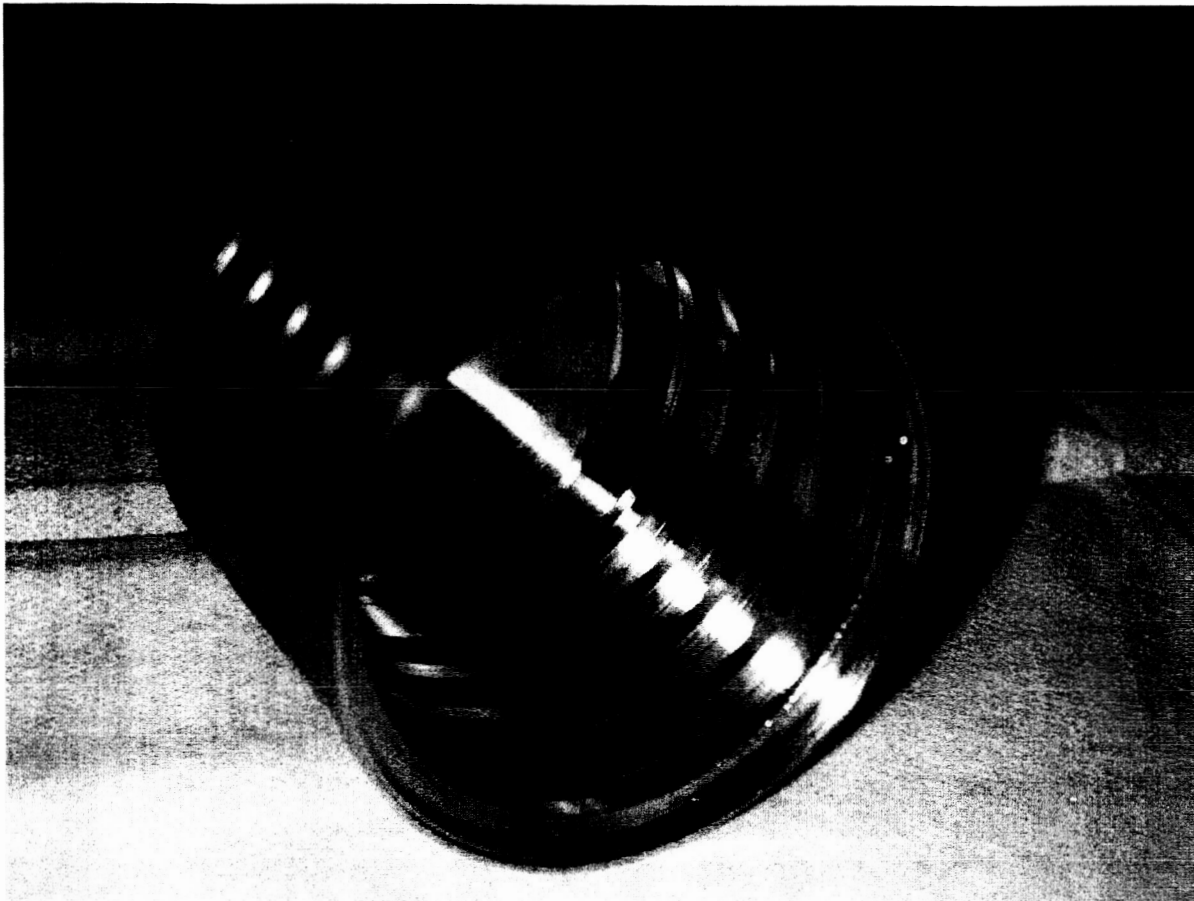
**Figure 11. Aluminum Dewar**



Rather than embarking on an potentially expensive and uncertain effort to improve the aluminum vacuum brazing process, a titanium Dewar design was developed that provided comparable thermal resistance to the heritage APL design with fewer parts and less mass. A highly innovative design using two Dewar cups that screw into each other was developed. One of these Dewar cups is shown in Figure 12.

**Figure 12. Titanium Dewar Prototype**

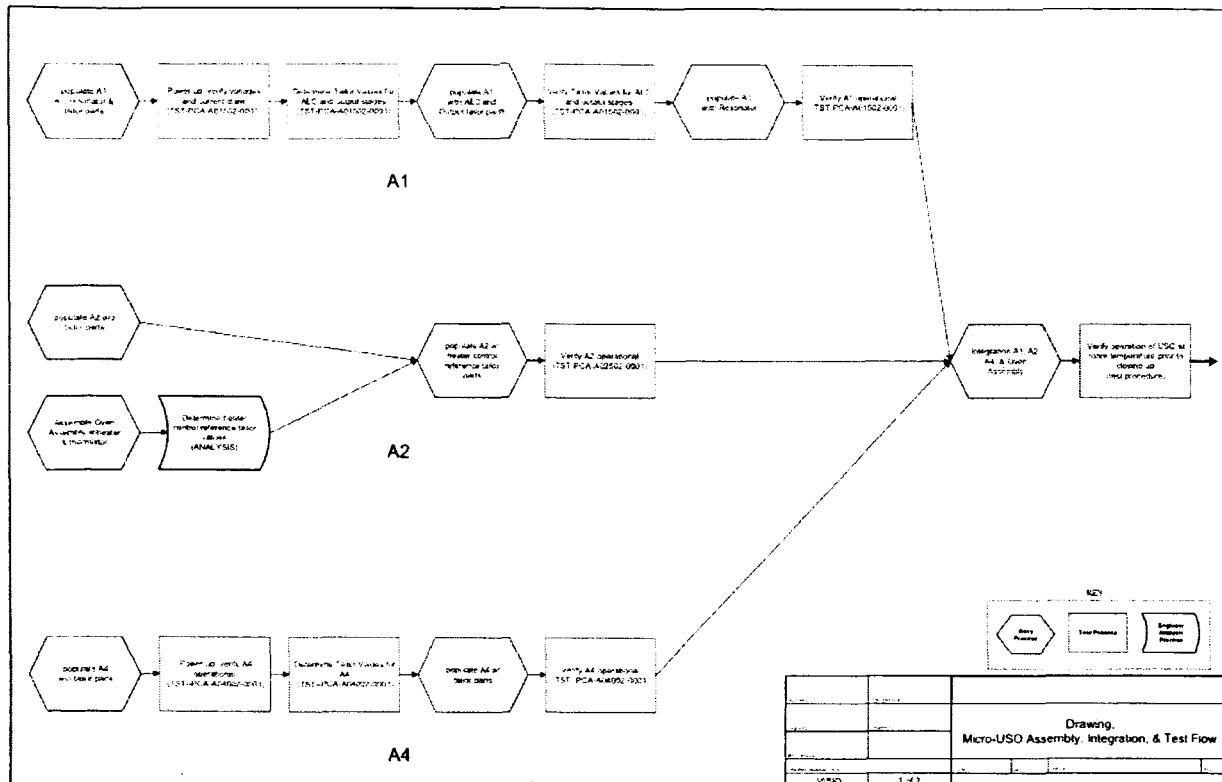
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**PHASE I TEST PROGRAM**

Figure 13 illustrates the Phase I test program.

**Figure 13. Phase I Test Program Flow**



Vibration testing was accomplished at APL. The Phase I prototype passed all qualification-level vibration tests. Appendices A and B provide the vibration and short-term stability test plans. (These plans are equally applicable to the Phase I and Phase II micro-USO designs.)

## **PHASE II MICRO-USO CONCEPTUAL DESIGN**

The Phase II micro-USO design focused on achieving a satisfactory thermal design without using a necessarily heavy and large (relative to the design goals) Dewar to isolate thermally the oscillator oven. The Phase II design insulates the oven by essentially eliminating heat conductive paths (very low conductivity threads are used to suspend the oven, so essentially all conductive heat transfer occurs along the wiring bundle from the oven to the housing) and by minimizing radiative heat transfer, by using a highly reflective oven suspended inside a highly reflective housing.

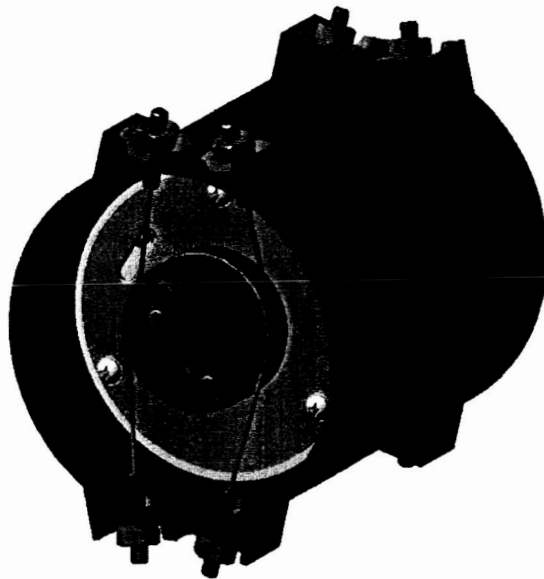
## Phase II Mechanical Design

The initial concept is shown in Figure 14 and Figure 15. The final mechanical design with a number of refinements to improve performance, ease of fabrication, and ease of assembly, is shown in Figure

16. The thread suspension system is proprietary to the Space Dynamics Laboratory (SDL) of Utah State. SDL supported the mechanical design and thermal analysis of the Phase II micro-USO.

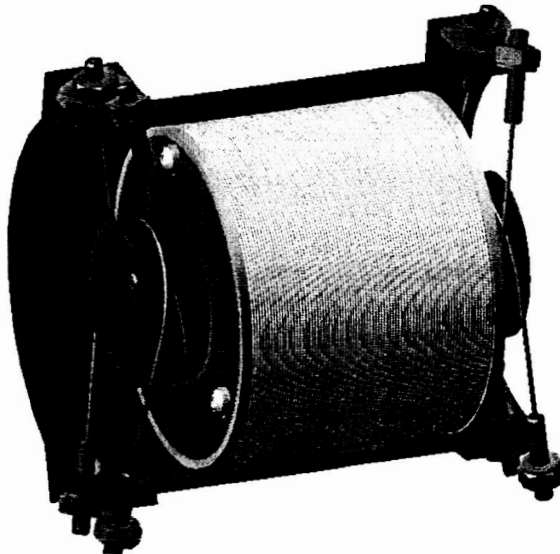
**Figure 14. Initial Design Concept of Phase II micro-USO (outside view)**

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**Figure 15. Initial Design Concept of Phase II micro-USO (cutaway view)**

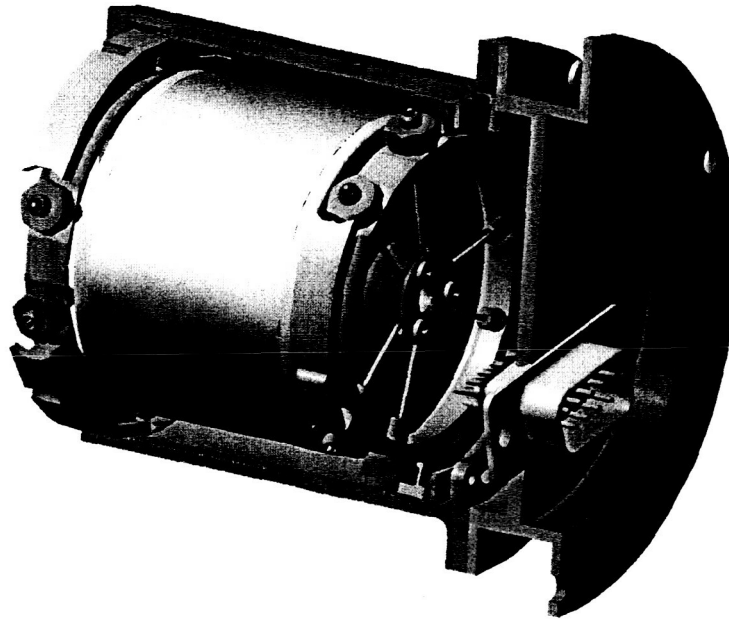
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**Figure 16. Final Design Concept of Phase II micro-USO (cutaway view)**

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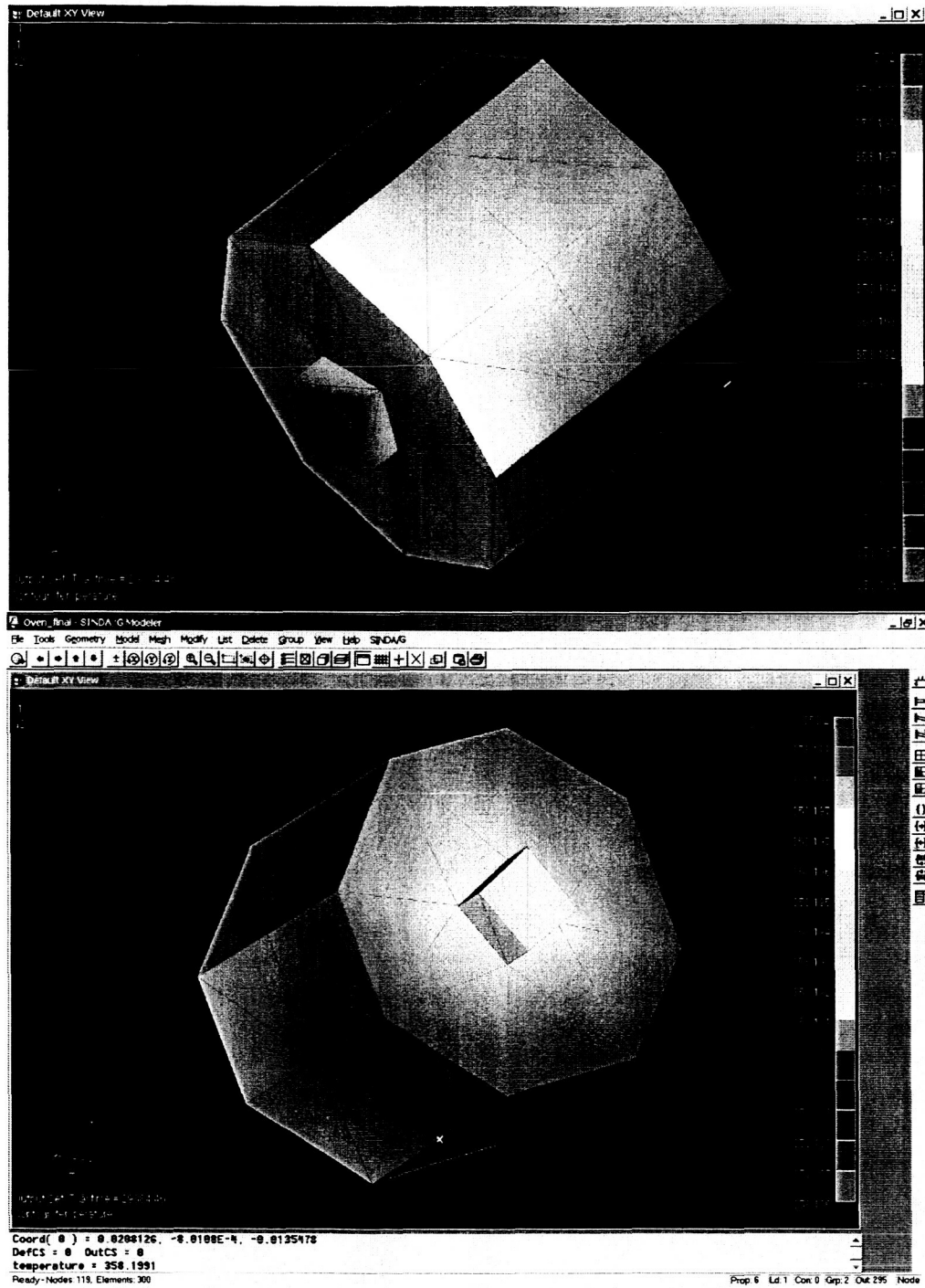


### **Phase II Thermal Analysis**

The thermal analysis of the Phase II design is extremely radiation intensive. To get the analysis to solve in one day per run, the thermal model was simplified and nodalized. The outer housing was meshed using shell elements, as the detailed heat flow in this structure is not as critical as the temperature-controlled oven. The oven was meshed using solid elements and the actual solid geometry from the design model. This allowed very accurate placement of the heater/temperature sensor, and to accurately model the radiation, suspension threads, and wiring heat load effects.

As is seen from Figure 17, the coldest node in the oven assembly is the wiring bundle attachment point (top view). This makes sense intuitively as well, as the largest conduction connection to the room temperature environment is thru the wiring. Another point that can be observed is how well the heater is maintaining temperature. This thermal model assumed a proportional heater control system that had a control resolution of  $\pm 0.05$  K around a nominal 358.15 K (85 C). Note that it is controlling well within the dead band of the system and is limiting the temperature change to less than  $\pm 0.003$  K, even though the environment is changing 30 K over the same time period. The thermal gradients in the oven are also small, which is desirable.

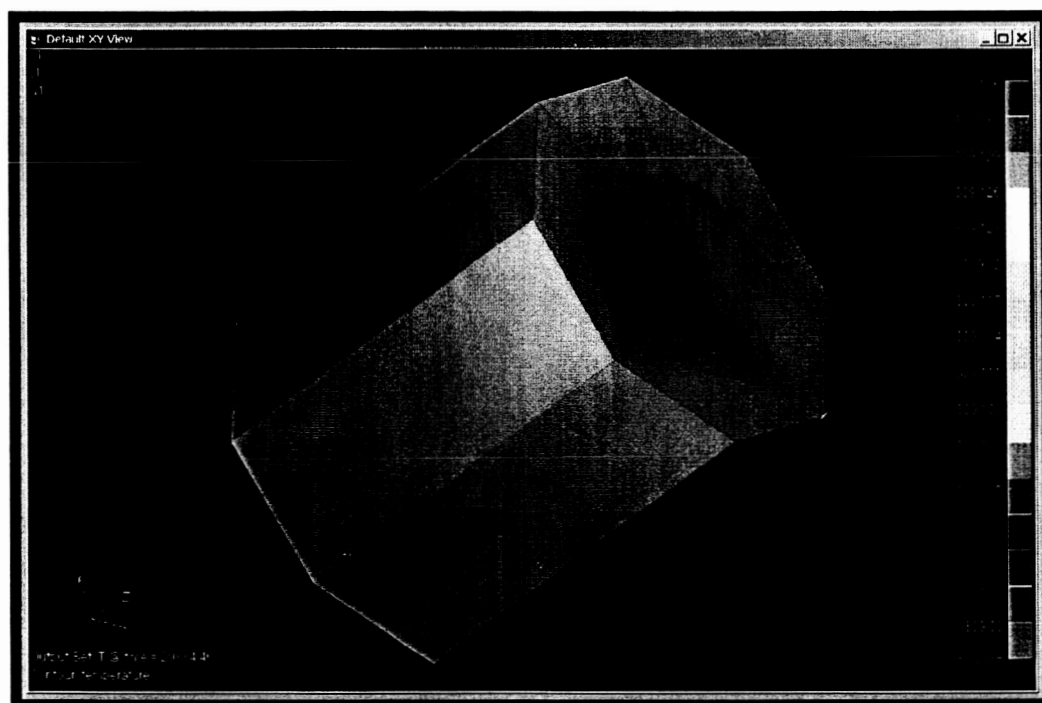
**Figure 17. Oven temperature gradients (hot case)**



As can be seen from the temperature legend in this figure, the maximum gradient across the oven is less than 0.014 K and the majority of that gradient is localized to where the wiring bundle is attached. The heat load effect from the suspension strings is so small that the effect is essentially negligible.

The temperature gradient in the outer housing for this case is shown in Figure 16.

**Figure 18. Outer housing temperature gradients (hot case)**



The red hot spot on the right side of Figure 18 shows where the wiring bundle is attached. The purple feature shown on the left side of the picture shows the effect on the gradient of one of the three thermal standoffs to the environment. Note the temperature gradient in the outer housing is small, slightly under 0.05 K. This analysis showed that in the hot case, the heat added by the heaters to the system to keep the oven at 358.15 K was approximately 118 mW. This is total heat input.

The lower emissivity of the cold case had a positive impact in most aspects of the thermal analyses. The heater control stability was improved, almost to a point of negligible drift. The gradients in the system were reduced. The outer housing had less average temperature rise, which essentially reduces the heater power needs. The steady state heat required by the heaters to maintain the oven at 358.15 K (85 C) in this case was approximately 36 mW.